DESIGN AND IMPLEMENTATION OF AN EXPERT SYSTEM FOR PROCESS PLANNING OF AXI-SYMMETRIC PARTS

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K. V. S. PRASAD

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CERTIFICATE

This is to certify that the present work on 'Design and Implementation of an Expert System for Process Planning of Axi-Symmetric Parts,' by K.V.S. Prasad has been carried out under my supervision and has not been submitted elsewhere for the award of a degree.

(Kripa Shanker)
Assistant Professor
Industrial and Management Engg.
Indian Institute of Technology,
Kanpur 208 016

February, 1987

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ABSTRACT

Computer-Aided Process Planning occupies a strategic position in the development of Computer Integrated Manufacturing Systems. Due to its importance, it is receiving the much deserved attention in the recent years. The recent developments in the Artificial Intelligence (AI) area saw the emergence of the concept of Expert Systems, which incorporate human experts knowledge for inference. An expert system for process planning of axi-symmetric parts has been developed. The features using which such a part can be described are identified. Once the part is described using the standard features, the system identifies the various operations to be performed, then sequences them and generates the process plan. Along with the sequence of operations, the recommended cutting conditions, tools, and cutting fluids are specified for each operation. The recommended single point tool angles, the total machining time and the time for which each tool is required are also specified. The system is capable of handling parts which can be described upto six features. It is built using an expert system shell, VIDHI on DEC-1090 at IIT, Kanpur.

CHAPTER I

INTRODUCTION

In the past few years there are certain startling and significant phenomena observed in the market behaviour of products. They are, a steady decrease of product life cycles, growing demand for shorter delivery times and stringent requirements on quality of the products. This trend promises to persist in future also. To keep up with these developments it is essential to have an industrial environment which is highly productive and at the same time flexible. Creating such an environment calls in for the employment of high level automation and expensive machine tools. Production Planning becomes vital in such a situation because one has to utilize the machine tools to the maximum possible extent and at the same time keep the stock levels and work-in-process inventory below a certain level, in order to operate economically.

There is a high degree of interdependency among machines, materials handling devices and other process resources which require a large number of timely decisions at the various levels of operations to be made. Typically, these decisions are based on large amounts of information and under time pressure. Due to the dynamic nature of the manufacturing environment

decision problems are often unstructured, and have to be continuously reviewed in view of the changing status of the system.

1.1 PROCESS PLANNING

1.1.1 Computer-Integrated Manufacturing Systems (CIMS)

To solve many of the problems mentioned above, concept of Integrated Manufacturing Systems has been developed which incorporates a real-time computer control system applied to integrate the different functions in the total manufacturing system. One way in which CIMS can be defined is, a system in which distributing computing network and common data bases are used for combining and coordinating into a harmonic whole such functions as product and process design, planning, scheduling, purchasing, production, inspection, assembly, handling, management and marketing of discrete consumer or producer goods.

The five main areas covered by Computer Control in CIMS are,

(i) Management Control

(ii) Computer-Aided Design

(iii) Computer-Aided Process Planning

(iv) Production Scheduling Control and

(v) Computer-Aided Manufacturing.

Industrial productivity can be increased to a larger extent if the two main areas, CAD and CAM are brought together

as close as possible. Computer-Aided Process Planning has the potential of becoming a vital link between CAD and CAM. Hence in the recent years considerable importance has been given to process planning in order to bridge the gap between CAD and CAM.

1.1.2 Understanding Process Planning

Process planning can be defined as the process of determining the methods and the sequence of machining a work-piece to produce a finished part or component to design specifications. In general, process planning has three steps involved which are selection, calculation and documentation. Selection involves the determination of appropriate processes, machine tools, tools, operations and sequences. Calculations must be done with respect to speeds, feeds, depth of cut, number of passes, machining time etc. And as a last step a route sheet has to be produced. In the route sheet the estimated or standard cycle time per piece and set-up time per lot are specified which in one way measure the performance expected.

1.1.3 Review of Various Process Planning Techniques

Traditionally process planning happened to be the job of an experienced engineer who used to draw the route sheets and drawings using his experience and judgement. Due to the difference of opinions among various planners, there used to be different routings depending upon the engineer. Arrival of

new machine tools used to render the old routings obsolete and considerable amount of time used to go into the preparation of new route sheets. Also machine break-downs used to force the workshop personnel to go in for temporary routings which were not necessarily optimal. All these difficulties are due to the inability to produce a route sheet in short interval of time. Hence these troubles paved the way for the emergence of Computer-Aided Process Planning which takes into account logic, judgement and experience and also produces route sheets in time.

The two major techniques of Computer-Aided Process Planning are,

(i) Variant type and

(ii) Generative type.

(i) Variant Type of CAPP Systems

Using the concepts of parts classification, coding and group technology, various parts that are produced in a plant are codified. Then for each part family, a standard process plan is established. When a part is given, using its code the nearest standard process plan is retrieved from the huge database and then is edited or modified according to the part in hand. Such a system is very useful but inelegant due to its huge storage.

(ii) Generative Type of CAPP Systems

Computer creates the process plan for any given part starting from scratch. It would employ a set of algorithms to progress through the various technical and logical decisions towards a final process plan. Such a system synthesizes the design of the optimum process sequence, based on an analysis of part geometry, material, and other factors which would influence manufacturing decisions.

1.1.4 Expert System for Process Planning

The concepts of generative process planning mentioned earlier have good potential as they can be used to any product at any time to produce the route sheet. But the problem is not so easy to be tracked down as there are no standard algorithms or methods. Most of the information or knowledge is empirical and to a large extent depends upon the type of industry, available machine tools and cutting tools. Also the logic in general is found to be complex and is not tractable to any algorithmic methods as it is too cumbersome, naive and inflexible. This logic and knowledge should be able to be easily modified or changed within the system.

Hence there seems to exist need to develop a system which is having the following characteristics:

(i) It should be possible to implement the company specific machining methods,

(ii) It should be possible to frequently evaluate and modify the decision criteria based on information obtained in manufacturing practice related to better methods and

(iii) It should be possible to maintain and develop company specific know-how in a practical way.

These characteristics can be realised in practice using some of the latest developments in Artificial Intelligence (AI) research. They are the knowledge based systems or the Expert systems. With the help of these recent AI techniques one can develop knowledge-base driven systems for process planning.

Artificial Intelligence can provide better planning and control towards a higher productivity of automatic manufacturing. In simple terms, some of the human intelligence which is needed to make decisions will be transferred to the computer machinery; many decisions will then either be made automatically, or information will be prepared for human operators to minimize delays in their decisions.

1.2 EXPERT SYSTEMS

Developments in the area of mathematical logic and computational methods which lead to symbol processing had a great impact on the recent AI techniques. These techniques paved way for the development of systems which incorporate some of the characteristics of human thought like the ability

to learn, reason, solve problems, and understand ordinary human language.

Research is going on and attempts are being made to develop a system which can duplicate the results of learned skills or expertise without concern for whether it is exactly the process used by real expert. The basic concern of such systems is to consistently duplicate the results of a human expert. Such systems are generally termed as Expert systems or Rule based systems.

1.2.1 Properties of Expert Systems

The properties shared by the various techniques of building expert systems are,

(i) Practical human knowledge is incorporated in the form of conditional rules,

(ii) Skill of the systems increase at a rate proportional to the size of the knowledge base,

(iii) Determine the best sequence of rules to execute, and

(iv) Explain their conclusions by retracing their actual lines of reasoning.

Because of the above properties, expert systems differ from traditional programs in both their architecture and in the development process by which they are constructed. In contrast to traditional programs, where the emphasis is on procedural instruction for the computer, the focus of expert

system development is on the acquisition and organisation of knowledge bases.

1.2.2 Features of an Expert System

As shown in Fig. 1.1, simple expert system consists of knowledge base and inference engine which are storage and processing elements, respectively [7]. The basic cycle of an expert system consists of a selection phase and an execution phase. During the execution phase, the system interprets the selected rule to draw inferences that alter the system's dynamic memory.

The knowledge base consists of domain specific knowledge in the form of rules and facts. The inference engine retrieves the facts and rules and using some resolution techniques tries to infer new goals. The control structure determines the way in which the rules and facts are linked. Some salient features of facts, rules and control structure are described below.

(a) FACTS: Facts are a kind of data in knowledge base, which express assertions about properties, relations, propositions etc. Facts are usually static and inactive.

(b) RULES: Rules always express a conditional, with an antecedent and a consequent component.

In general the production rules are expressed as,

IF <antecedent>

THEN <consequent>.

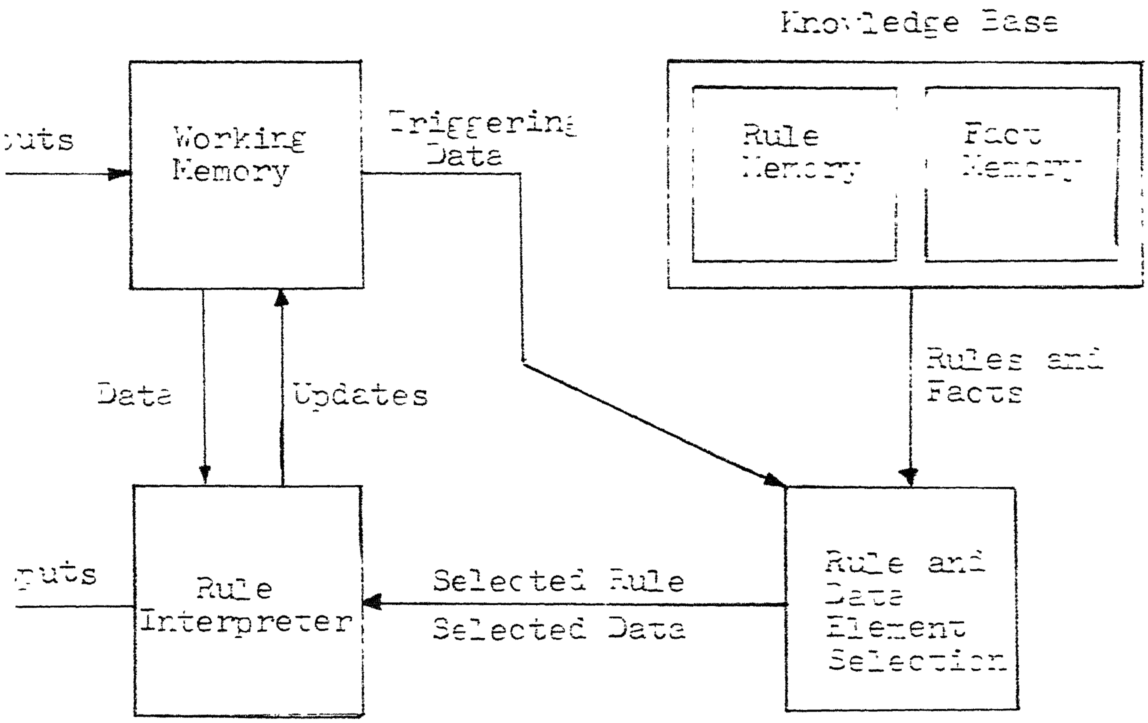

Fig. 1.1: Structure of an Expert System.

The interpretation of a rule is that if the antecedent can be satisfied the consequent can also be satisfied. Rules always specify analytic problem solving knowledge and they form the basis for inference mechanism.

(c) CONTROL STRUCTURE: This defines the problem solving approach or how the data and knowledge can be manipulated to solve the problem. This control strategy is a function of the problem to be solved. The general approaches are,

(i) Forward Chaining: If the solution starts from an initial set of data and conditions and moves towards some goal or conclusion, it is called model, data, event or antecedent driven.

(ii) Backward Chaining: In this method, expert system begins with a goal and successively examines any rules with matching consequent components. These candidate rules are considered one at a time. The unmet conditions of the antecedent are extracted from each plausibly applicable rule, and these conditions are in turn defined as new goals. The back chaining control then shifts attention recursively toward the new goal. The effort terminates when the top goal has been reduced to a set of satisfied subgoals.

1.2.3 Knowledge Representation:

Power of any expert system lies in its specific knowledge of the problem domain. This domain knowledge is usually procedural in the sense that it tells how the data for a problem can

be manipulated in order to solve the problem. There are various schemes using which this knowledge can be represented. They are,

(i) Predicate logic
(ii) Procedural construction
(iii) Semantic networks
(iv) Production systems and
(v) Frames.

1.2.4 Expert System Shell, VIDHI

VIDHI, is an expert system shell developed at IIT, Kanpur based on logic programming fundamentals. The logic programming is based on a subset of first-order predicate calculus namely the horn clauses.

(i) LOGIC PROGRAMMING

Logic Programming can be used to solve problems involving objects and relationships. Predicates are used to express the relationship between objects. For example, to express Ram is heavier than Tom, one can define a predicate heavier and represent it as:

(HEAVIER RAM TOM)

Rules are framed using atomic formulas which consist of predicates and terms. These rules are used in inferring new goals. Here we shall briefly discuss what is meant by terms, atomic formulas and inference.

(a) TERMS: Terms occur as arguments of predicates in formulas and usually denote things. A term can be any one of the following:

1. a variable : a symbolic atom beginning with a '?' (e.g., ?Y, ?TYPE)
2. a constant : a symbolic atom not beginning with a '?' or a number (e.g., 7, TAPER),
3. a function-arguments combination : a list of the form

   (<f><pl> ... <pn>)

where <f> is a function symbol and <pl> to <pn> are arguments. Hence a function GET-THEM defined over two arguments RAM, SAM written as (GET-THEM RAM SAM) can be a term.

(b) FORMULAS: A formula can take any one of the following two forms:

1. An atomic formula is a predicate-arguments combination where the predicate is a symbolic atom, and the arguments are terms. It is represented as a list.

   (TAPSPD PCLS 175225 160)

   where TAPSPD is the predicate and PCLS, 175225, 160 are arguments.
2. A horn clause is of the form,

   $$B \leftarrow A_1 \ldots A_n, \quad n >= 0$$

   where B and A_1 to A_n are atomic formulas. B is called the consequent and A_1 to A_n antecedent. If the antecedent is empty (i.e.) n = 0, the horn clause reduces to an atomic formula.

For example, if one wants to say every ?X father of ?Y is a parent of ?Y as well, it can be represented as,

(PARENT ?X ?Y) ← (FATHER ?X ?Y)

A horn clause with an empty antecedent is called a fact while one not so is called a rule. Normally, rules have variables, while facts do not have any.

A formula whose truth value is to be determined is called a query or a goal formula. If the goal formula has a variable, then the binding of the variable for which the formula is true is the answer. If the formula cannot be proved true for any of the binding the answer is false.

(c) INFERENCE: The inference mechanism starts when a goal or a query is posed by the user. The inference proceeds by modus ponens (i.e.), by application of rules.

First, we check whether a query or goal matches with a fact already present. If yes, the query can be answered to be true. In case the query fails to match with any of the facts, we try matching it with the LHS of rules. If a rule matches, the atomic formulas in its RHS after proper instantiation become the new sub-goals, all of which have to be matched as above. In case of failure to match a sub goal, another rule is fired. This process repeats until either we are successful, or no more rules remain to be tried.

(ii) OTHER FEATURES:

The shell provides an ASK-USER predicate which facilitates in posing questions to the user. If the user is unable to provide the answer the formula is not true and it is recorded that the user does not know the answer. If the formula is satisfied an appropriate fact is asserted.

It is possible to declare some of the predicates as of intermediate type if they are to be asserted as facts in case they get inferred. Similarly text can be attached with predicates so that it will help the user in answering some of the questions.

For a detailed explanation of the VIDHI shell, one is referred to the Tutorial on VIDHI, which is available on DEC-1090 at IIT Kanpur. Various commands and usage of the VIDHI shell along with the manuals are given in Appendix A.

CHAPTER II

LITERATURE REVIEW

Developing a system which can perform process planning automatically is becoming more and more important. With the advent of FMS technology and new manufacturing methods, process planning is getting the much deserved attention due to its potential in linking CAD and CAM to produce a high productivity industrial environment.

2.1 CAPP SYSTEMS

Weill et al., and Eversheim et al., developed Computer-Aided Process Planning (CAPP) systems for rotational, sheet-metal and Prismatic Parts [6]. These systems are basically developed using variant approach. They store standard process plans based on part family and group technology concepts. Whenever a part is given, using its classification code the standard plan is retrieved and edited depending to suit the part. There are systems available which develop the process plans by interaction with the user. One such system is ICAPP developed by Eskicioglu and Davies, which uses both variant and generative methods [5].

2.2 EXPERT SYSTEMS AND PROCESS PLANNING

There have not been many systems developed based on the concepts of generative approach because of the natural

difficulty in incorporating the logic and judgement. With AI techniques rapidly growing, there are few attempts made in developing expert systems for process planning which use the expertise and knowledge of skilled process planners.

Systems developed by Matsushima et al., and Van't Erve et al., [1,3] use production rules for representing the knowledge as rules and facts. The production rules are generally conditional and they are of If-then form.

IF <consequent geometry>
AND < - - - - - - - - - - >
OR < - - - - - - - - - - >
:
THEN <recommendable machining type>
<specified parameter and its value>
:
<antecedent geometry>

In one of the systems developed by Davies and Derbyshire,[2] fuzzy logic is used in representing the rules. A fuzzy logic rule introduces an element of uncertainty and has the form,

If <to a certain extent> <condition>
then <to some degree> <action>

Invariably, the control strategy in all these systems is one that uses back-tracking search or goal hypothesis. In all these systems there are some standard features, or clauses defined in order to specify the product. But these features

are generally incomplete and primitive in nature. They also provide with the concept of generating alternate routings which are to be evaluated on some economic criterion to choose the best one. Systems described in [1,3] are basically suited for drilling holes while the one, in [2] is suited for rotational parts.

There has been an expert system developed for machining data selection by Wang and Wysk [4] which uses both empirical equations and stored data in database. This system uses a forward reasoning scheme. The user enters the combination of material, tool, operation etc., the recommended machining data will then be generated and presented on the screen.

So far the expert systems developed in this area use the conventional programming languages like Fortran and Pascal. Hence the efficiency of such systems while pattern matching are found to be limited. Using languages like LISP and PROLOG wil improve the system's performance as well as the inference mechanism.

2.3 SCOPE AND ORGANISATION OF THE WORK

In the present work an expert system has been designed and developed for process planning of axi-symmetric parts. Given the description of the part in terms of features, the system identifies the operations, generates the operation sequence and determines the cutting conditions. In addition,

it also recommends the cutting tools and cutting fluids. The system also generates various statistics such as machining time and the time required for each tool. Such statistics can be used for production planning and scheduling. In the Chapter III, we will discuss the design of the expert system, where in various modules of the system are explained along with their functions. Chapter IV presents the formulation of various rules and facts that generate the process plan. A sample output demonstrating the consultation with the system and various system capabilities is also included. Chapter V concludes the work and presents the scope for future work.

CHAPTER III

DESIGN OF THE EXPERT SYSTEM

The design of the expert system involves as a first step, acquisition and collection of knowledge from experts as well as from hand books. Then, this acquired knowledge has to be structured and organised into well framed facts and rules which form the basis for inferring new goals. To formulate the facts and rules it is essential to think of the right kind of predicates to represent various relationships between objects. Identification of the various features, using which one can define a product, happens to be an important step in the design because it helps the user to define the product completely.

In the present work we confine ourselves to axi-symmetric parts. Axi-symmetric parts are those whose surface to be formed is symmetrical about the axis of rotation. We consider engine lathe and centre lathe as the two machine tools, using which the part can be produced. The design can be easily modified to suit for turret and capstan lathes.

3.1 SYSTEM DESCRIPTION

The block diagram of the system is as shown in the Fig. 3.1.

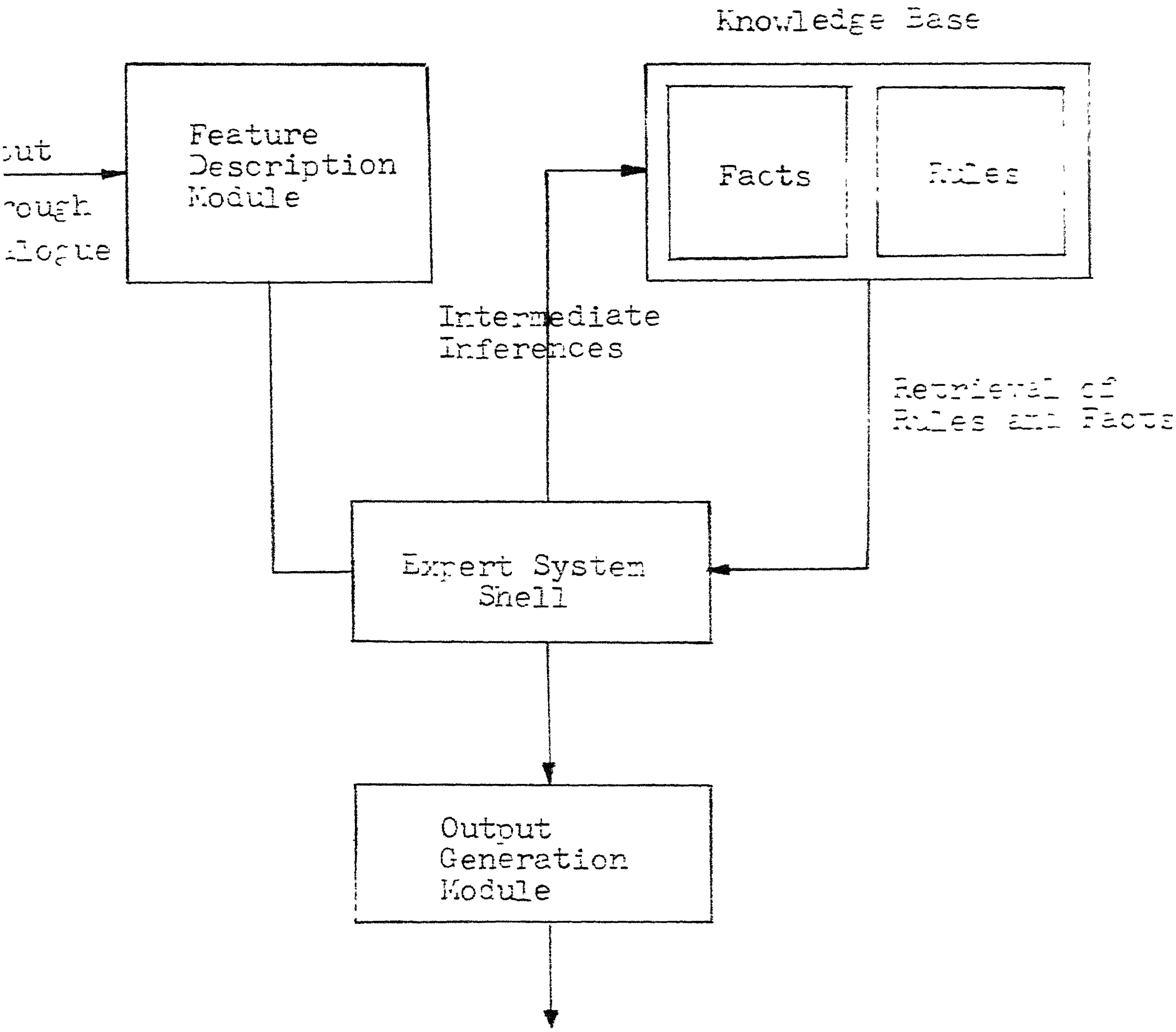

Fig. 3.1: Structure of the system.

The feature description module, through a dialogue with the user gets the complete information about the part. The shell, in the process of satisfying the goal of developing the process plan, triggers various facts and rules available in the knowledge base and infers various sub-goals. If some of these sub-goals which are useful in future can be defined to be of intermediate type and added to the knowledge base of facts, it will reduce the labour of inferring them in future. The output generation module takes up some of these inferred sub-goals and develops the route sheet along with the recommended cutting conditions, tools and cutting fluids.

3.2 FEATURE DESCRIPTION MODULE

It is essential that every part is completely described. This helps the computer in understanding the part in hand. In order to achieve the above objective there have been some standard features identified in case of axi-symmetrical parts, which are given below.

1. FACE - any surface that is perpendicular to the axis of rotation
2. CYL - any cylindrical surface
3. EXTAPER - any external tapering surface
4. INTAPER - any internal tapering surface
5. EXTHREAD - any portion of the surface that is threaded externally

6. INTHREAD - any portion of the surface that is threaded internally
7. HOLE - any internal cylindrical surface
8. KNURL - any portion of the surface that is knurled
9. FORM - any surface that is curved in nature

Features are characterized by shape definition, geometrical and technical data. Hence for a complete description of the features Table 3.1 may be referred to. Along with the feature description, the data regarding the surface finish and tolerance is also to be supplied.

3.3 THE KNOWLEDGE BASE

The human expert's knowledge generally tends to be unstructured and fragmented. The design involves organisation of such knowledge and representation in the form of facts and rules.

3.3.1 FACTS:

A fact is defined as an unconditionally true assertion, hence it is a rule with a nil antecedent. The various facts that are framed in this present system correspond to the recommended cutting conditions for various operations, recommended cutting tools, recommended single point tool geometry and the cutting fluids for various operations. Facts are to be designed by identifying the right type of predicate along with the necessary arguments or terms. The two aspects

Feature	Part Produced from Bar Stock			Part Produced from Casting		
	Geometrical and Technical Data			Geometrical and Technical Data		
FACE	Distance from the reference end	Outer diameter	Inner diameter	Casting outer diameter	Required outer diameter	Required inner diameter
CYL	Distance from the reference end	Length	Diameter	Casting diameter	Length	Required diameter
EXTAPER, INTAPER	Diameter nearer to the ref. end	Length of tapering	Other diameter	Casting larger diameter	Length	Required larger diameter
EXTHREAD, INTHREAD	Nominal diameter	Length of threading	Pitch of thread	Nominal diameter	Length of threading	Pitch of thread
KNURL	Distance from the reference end	Length of knurling	Diameter	Casting diameter	Length of knurling	Required diameter
FORM	Distance from the reference end	Length of forming	Largest diameter of the feature	Distance from the reference end	Length of forming	Largest diameter of the feature
HOLE	Required diameter	Length	Distance from the reference end	Required diameter	Length	Casting diameter

Table 3.1: Feature Input Details.

that are to be kept in mind while forming the facts are the reduction in redundancy and the increase in flexibility.

3.3.2 RULES:

A rule is an assertion which forms sub-goals when the consequent matches with the goal. These sub-goals become goals in the next stage. This process continues until either the database is exhausted or all the sub-goals are satisfied. Each rule says that if the consequent goal or situation has to be satisfied all the antecedents have to be satisfied. The rules that are framed in the present system aid in generating the sequence of operations, determining the necessary cutting conditions, selecting the cutting tools, recommended single point cutting tool geometry and the cutting fluids for each operation.

While framing the rules, it is necessary to envisage all kinds of products that can be formed using the features described earlier. Ordering of the rules happens to be an important step. As the goal is matched with the consequent of a rule sequentially, ordering becomes vital. If the ordering is improper either system will go into an infinite loop or it will infer something irrelevant. Rules are to be precise and distinct.

3.4 THE OUTPUT GENERATION MODULE

When the top goal i.e., developing a process plan has been requested, the system tries with various facts and rules and satisfies a number of sub-goals to infer the top query. These sub-goals if they are defined to be of intermediate type, get asserted and stored in the fact data base. To generate a detailed report, it is essential to get them from the fact database where they are stored as property lists. Using these facts various reports are generated. The sequence of operations, the cutting conditions which include speed, feed, depth of cut, number of passes along with machining time, the recommended cutting tools for each operation along with their equivalent ISI code, the recommended single point cutting tool geometry and the cutting fluids for each operation. Another report which specifies for how much time each tool isrequired is also generated. This report gives an idea about how much time each tool is tied up and also helps in tool planning on a wider horizon.

CHAPTER IV

DEVELOPMENT AND IMPLEMENTATION OF THE EXPERT SYSTEM

This chapter deals with the implementation of the system and also gives the goal tree generated when the top query of process plan is requested. At the end of this chapter, a sample output is attached which brings out the system capabilities.

4.1 REPRESENTATION OF FACTS

In the knowledge base, there are facts stored relating to various cutting conditions (speed, feed, depth of cut) and tool angles (Back rake, Side rake, End relief, Side relief, Side and Cutting edge angles). In this section we shall discuss how the various facts are represented which facilitate the inference of new goals. We consider them group-wise.

4.1.1 Rough Turning, Rough Boring and Rough Taper Turning:

The predicate with which the cutting data corresponding to speed, feed and depth of cut for the above operations linked with is SRCDAT and the fact is represented as,

```
(SRCDAT material ((((HSS-speed range-1)(Carbide-speed range-1))
                   (Feed range-1)(Depth of cut range-1))
                  (((HSS-speed range-2)(Carbide-speed range-2))
                   (feed range-2)(Depth of cut range-2))))
```

(e.g.) (SRCDAT FCS ((((110 40)(250 150))(0.3 0.2)(2 0.5))
(((70 40)(180 120))(0.5 0.25)(5 2))))

represents ranges of speed, feed rate and depth of cut as mentioned within the parenthesis.

4.1.2 Finish Turning and Finish Boring:

The predicate with which the cutting parameters for operation finish turning is linked with is SFCDAT and the one for finish boring is BFCDAT. The structure of the both the facts look alike. They are represented as,

(SFCDAT material Hardness range
(HSS-speed HSS-feed HSS-depth of cut)
(Carbide-speed Carbide-feed Carbide-depth of cut))

(e.g.) (SFCDAT PCLS 125175 (38 0.18 0.64) (151 0.18 0.64))
(BFCDAT HSTS 175225 (15 0.10 0.25) (60 0.13 0.25))

4.1.3 Drilling and Reaming:

The predicate used for storing drilling data is DRLDAT and for reaming it is REMDAT. The feeds corresponding to the standard drills whose diameters are 1/8", 1/4", 1/2", 3/4", 1", $1\frac{1}{2}$" and 2" are stored and for any other drill falling in between, the feed is interpolated. The representation looks like,

(DRLDAT material Hardness-range

(Speed (Various feeds corresponding to standard drill

(e.g.)

(DRLDAT MTS 225275 (10 (0.05 0.08 0.13 0.23 0.25 0.30 0.33)

(REMDAT MTS 225275 (9.5 (0.05 0.13 0.25 0.41 0.51 0.64))).

4.1.4 Tapping:

The predicate that is defined is TAPSPD and the representation is,

(TAPSPD material Hardness-range speed)

e.g.,

(TAPSPD ASS 175225 4.7)

4.1.5 Thread Cutting:

Thread cutting data is represented using the predicate THRDAT as,

(THRDAT nominal-diameter pitch of the thread

(Spindle speed   No. of cuts if external threads   No. of cuts if internal threads))

e.g.,

(THRDAT 48 3 (315 10 13))

4.1.6 Cutting Fluids:

The cutting fluid to be used depends to a large extent on the operation being performed and workpiece material. The data regarding the cutting fluid has been linked with two predicates FLDCODE and FLDNAME. They are represented as,

(FLDCODE operation material cutting fluid code)

(FLDNAME cutting fluid code cutting fluid name)

e.g.,

(FLDCODE REAM ASS 4)

(FLDNAME 4 (HIGH SULPHUR FATTY CHLORINATED OIL))

Similarly, there are predicates defined associated with facts for other operations like facing, counter boring, counter sinking, knurling and form turning. Also there are facts stored corresponding to cutting tools alongwith their I.S. Code for various operations and also the recommend single point tool angles depending upon the tool material. There are more than 350 facts stored in the present fact database. All these data have been compiled using various handbooks [9,10,11].

4.2 REPRESENTATION OF RULES

Rules are represented as,

$$B \leftarrow A_1, A_2, \ldots, A_n$$

where $B, A_1, \ldots, A_n$ are atomic formulas as described earlier.

The rules framed are dependent on the logic. The logic is due to technological considerations and operations feasibility. The rules when fired succeed in inferring some goals which determine the sequence of operations.

Before, the rules are framed, it is essential to envisage all the parts that can be defined with a certain

number of features, and place them in one category. Thus the parts are categorized as three feature parts, four feature parts and so on. The number of sub-goals that will be set-up are different for each category of parts, which basically depends on the maximum number of operations into which the features get exploded.

For example, let us take the rules relating to four feature parts and see how they look like. There are predicates OPR41, OPR42, ..., OPR48 which basically determine the sequence of operations. Such type of predicates are here onwards referred to as output predicates. The atomic formula involving output predicate will generally be present as a consequent in all the rules. Before a formula involving output predicate gets asserted, it forms the formula having data predicate, such as DAT41, DAT42,..., DAT48 as sub-goal. This makes it possible to assert both the operation and its corresponding data. For example,

```
(OPR43  CYL  ROUGH  2  ?FX3  ?FY3  ?FZ3) ←
                        (BAR-STOCK)
                        (OP2 CYL ?X3  ?Y3  ?FZ3)
                        (LENGTH  ?FY3)
                        (BAR  ?FX3)
                        (DAT43  RCYL  ?SFD43)
```

This rule states that the operation is rough turning corresponding to feature number 2, provided the second feature is CYL and the part is produced from Bar Stock. Note the formula having data predicate DAT43 which is asserted before the operation is inferred. The output predicate OPR43 carries information regarding what type of an operation, what feature does it correspond to and what are the dimensions. The dimensions help in calculating the spindle speed, depth of cut, number of passes and hence the machining time. Here we shall discuss the formulation of various rules.

FACING:

Invariably, whenever a part is produced from bar stock it is essential that the end is faced which helps in centering. Centering is essential for controlling various diametrical dimensions of the part being produced.

```
(OPR61 FACE RH 6 ?FX1 ?FY1 ?FZ1) ← (OP6  FACE ?FX1 ?BY1 ?FZ1)
                                   (OP1  FACE  ?X1  ?Y1  ?Z1)
                                   (BAR  ?FY1)
                                   (DAT61  FACE ?C1)

(BAR ?FY1)  ←  (MAX-DIA   ?MD)  (BSIZE  ?MD   ?FY1)
(BSIZE  ?A  ?B)  ←  (ASK-USER  (SOURCE  ?A)
                              (TARGET  ?B)
                              (QUESTION PLEASE SPECIFY THE NEAREST
                              BAR DIAMETER CORRESPONDING TO A SIZE
                              OF  ?A))
```

(DAT61 FACE ?C1) ← (TOOL-MTL CARBIDE)
(MATERIAL ?M)
(HARDNESS ?H)
(SFCDAT ?M ?H ?X ?C1)

When the facing is performed first, the diameter size over which the operation is done corresponds to original bar stock size. The rule also says that if the sixth feature is facing and the first feature is facing, then satisfy this rule. This is because there can be facing operations corresponding to features two and three.

Whenever, we talk about facing it is not only corresponding to the ends but also to any surface that is perpendicular to the axis of rotation. These surfaces can be either a collar surface or a shoulder surface. When operation is performed on such surfaces it is required to know whether a RH facing tool is to be used or a LH facing tool is to be used. In the above rule, if the consequent is observed one can see that there is a term RH which means a RH facing tool is specified.

ROUGH TURNING:

Any surface that is specified with the help of features like CYL, EXTHREAD, KNURL and sometimes EXTAPER require that a primary operation of rough turning to be performed. If a part is described with the help of some of the features mentioned

above, it is necessary that rough turning is performed corresponding to these features. Whenever, rough turning is to be performed related to two or more than two features, it is recommended that they are performed in a sequence because the tool to be used in all these cases remains the same. This helps in saving time related to setting up of the tool.

```
(OPR63  CYL  ROUGH  2  ?FX3 ?FY3  ?FZ3) ← (OP2  CYL  ?X3  ?Y3 ?FZ3)
                                          (BAR  ?FX3)
                                          (LEN-DIS  ?FY3)
                                          (DAT63  RCYL ?C3)
(OPR63  CYL  ROUGH  2  ?FX3  ?FY3  ?FZ3) ← (OP2 KNURL ?X3 ?Y3 ?FZ3)
                                          (BAR  ?FX3)
                                          (LEN-DIS ?FY3)
                                          (DAT63  RCYL ?C3)
(OPR63  CYL  ROUGH  5  ?FX3  ?FY3  ?FZ3) ← (OP5 EXTHREAD ?FZ3 ?Y3 ?F
                                          (BAR ?FX3)
                                          (LEN-DIS ?FY3)
                                          (DAT63  RCYL ?C3)
(LEN-DIS  ?LD)  ←  (ASK-USER  (SOURCE)
                              (TARGET ?LD)
                              (QUESTION PLEASE SPECIFY THE TOTAL
                              LENGTH OF THE PART THAT IS PRODUCED))
(DAT63  RCYL  ?C3) ← (MATERIAL  ?M)
                     (SRCDAT ?M  ?C3)
```

The rough turning operation when done initially requires that the whole length of the work piece to be turned. Also the thickness of material that is to be removed depends on the original bar stock size and the required diameter. Hence this information regarding bar size and the total length is passed to the consequent as shown in the above rules.

FINISH TURNING:

A finish turning operation is required to be performed on any surface only if the surface roughness specified on that particular surface is less than 125 micro inches. Also since we are asking the user to specify 0 if he does not know the surface roughness value, we should check for the condition of surface roughness being greater than 0.

```
(OPR67  CYL  FINISH  5  ?FZ7  ?FY7  ?FX7)  ←  (OP5  CYL  ?FX7  ?FY7  ?FZ
                                              (OP2  FACE  ?X7  ?Y7  ?Z7)
                                              (ST7  ?S7  ?T7)
                                              (> ?S7  0)  (< ?S7  125)
                                              (DAT67  FCYL  ?C7)
(DAT67  FCYL  ?C7)  ←  (TOOL-MTL CARBIDE)
                       (MATERIAL  ?M)
                       (HARDNESS  ?H)
                       (SFCDAT  ?M  ?H  ?X  ?C7)
(DAT67  FCYL  ?C7)  ←  (TOOL-MTL  HSS)
                       (MATERIAL  ?M)
                       (HARDNESS  ?H)
                       (SFCDAT  ?M  ?H  ?C7  ?X)
```

```
(TOOL-MTL  ?TM) ← (ASK-USER  (SOURCE)
                             (TARGET  ?TM)
                             (QUESTION PLEASE SPECIFY THE TOOL
                              MATERIAL THAT IS BEING USED))
(DEFELAB  TOOL-MTL  (IT IS RECOMMENDED THAT CARBIDE TOOL MATERIAL
                     IS USED FOR OPERATIONS LIKE TURNING, TAPERING,
                     THREADING AND FACING.  WHILE FOR OPERATIONS
                     LIKE BORING, DRILLING AND REAMING HSS TOOLS
                     ARE PREFERRED)).
```

One more point to be noted is that the data that is getting asserted depends on the tool material that is specified by the user.

ROUGH TAPER TURNING, FINISH TAPER TURNING AND CHAMFERING:

The structure of the rules for identifying this type of operations remains to be the same as one described earlier for rough turning and finish turning, but for one additional predicate TAPER. This predicate tries to establish whether the operation is performed using a form tool, which is one way of producing the taper. This is useful because, the way in which feed and depth of cut are specified for form tools are different from the way in which they are specified for other ways of production.

```
(OPR67  REXTAPER  ?TYPE  5  ?FX7  ?FY7  ?FZ7) ←
                              (OP5  EXTAPER  ?FX7 ?FY7  ?FZ7)
                              (>  ?FY7  6)
                              (OP3  EXTAPER  ?X3  ?Y3  ?Z3)
                              (TAPER  5  ?TYPE)
                              (DAT67  REXTAPER  ?C7)
(OPR68  FEXTAPER  ?TYPE  5  ?FX8  ?FY8  ?FZ8) ←
                              (OP5  EXTAPER  ?FX8  ?FY8  ?FZ8)
                              (OP2  FACE  ?X2  ?Y2  ?Z2)
                              (ST5  ?S5  ?T5) (>  ?S5  0)(<  ?S5  125)
                              (DAT68  FEXTAPER  ?C8)
(TAPER  ?A  ?B) ← (ASK-USER  (SOURCE  ?A)
                              (TARGET  ?B)
                              (QUESTION PLEASE SPECIFY FORM IF
                              THERE IS A FORM TOOL AVAILABLE SO
                              THAT FEATURE  ?A  CAN BE PRODUCED
                              BY FORM TURNING ELSE SPECIFY OTHER))
```

Checking for the length of tapering being greater than 6 mm helps in distinguishing between taper turning operation and chamfering operation. If it is a chamfering operation, the operation may get delayed and come late in the sequence of operation as another tool like chamfering tool has to be loaded for producing this operation.

```
(OPR610  CHAMFER  DUM  5  ?FX10 ?FY10 ?FZ10) ←
                                 (OP5  EXTAPER  ?FX10 ?FY10 ?FZ10)
                                 (<= ?FY10  6)
                                 (OP1  FACE  ?X1 ?Y1 ?Z1)
                                 (DAT610  CHMF  ?C10)
```

DRILLING:

Whenever a part is produced from bar stock which is having a feature as HOLE, it is required that the drilling operation is performed. If it is produced from casting, it is likely that it has a hole already cast. Otherwise in such case one can use core drills which are specially meant for enlarging the holes. It is also necessary that, if the feature is INTHREAD, drilling operation is performed initially.

```
(OPR67  DRILL  ?DIA  1  ?FX7  ?FY7  ?FZ7) ←
                                 (OP1  HOLE  ?FX7  ?FY7  ?FZ7)
                                 (DSIZE  1  ?DIA)
                                 (DAT67  DRILL  ?C7)
(OPR67  DRILL  ?DIA  1  ?FX7  ?FY7  ?FZ7) ←
                                 (OP1  INTHREAD  ?FX7  ?FY7  ?FZ7)
                                 (DSIZE  1  ?DIA)
                                 (DAT67  DRILL  ?C7)
(DSIZE  ?A  ?B) ← (ASK-USER  (SOURCE  ?A)
                                 (TARGET  ?B)
                                 (QUESTION  PLEASE SPECIFY THE NEAREST
                                 STANDARD DRILL SIZE CORRESPONDING TO
                                 A DIAMETER OF  ?A))
```

(DEFELAB DSIZE (THERE ARE STANDARD DRILLS AVAILABLE RANGING
FROM A SIZE OF 3 MM TO 50 MM WITH AN INCREMENT
OF 0.5 MM)).

ROUGH BORING:

If the hole that is produced by a drill has to be enlarged or if the hole that is produced by casting has to be brought to a required size then the operation of rough boring is specified. The data related to rough boring and rough turning remains the same as both are basically turning operations.

```
(OPR68  BORE  ROUGH  1  ?FX8 ?FY8 ?FZ8) ←
                                (OP1  HOLE  ?FX8  ?FY8  ?FZ8)
                                (DSIZE  1  ?FZ8)
                                (DAT68  RBORE  ?C8)
```

REAMING AND FINISH BORING:

Reaming and finish boring, both the operations are finishing operations which help to achieve the required dimensional tolerance. But to know when to use which operation is interesting. The reamer size is one limitation while the other limitation is the length to diameter ratio. The reamers are available, in general, from 3 mm to 40 mm. If the diameter is larger than this one has to go in for boring operation. Also another consideration is that if the length to diameter ratio is less than 2 reaming is preferred to boring. In the present work we incorporated the second consideration.

```
(OPR69  BORE  FINISH  1  ?FX9  ?FY9  ?FZ9) ←
                                  (OP1  HOLE  ?FX9  ?FY9  ?FZ9)
                                  (BORE-OR-REAM ?FX9  ?FY9)
                                  (OP3  FACE  ?X3  ?Y3  ?Z3)
                                  (ST1  ?S1  ?T1) (> ?S1  0) (< ?S1  12
                                  (DAT69  FBORE ?C9)
(DEFCOMP  BORE-OR-REAM (LAMBDA (X Y) (COND [(< X (*  2  Y)) T]
                                              [T  NIL ])))
(OPR69  REAM  ?SIZE  1  ?FX9  ?FY9  ?FZ9) ←
                                  (OP1  HOLE  ?FX9  ?FY9  ?FZ9)
                                  (OP3  FACE  ?X3  ?Y3  ?Z3)
                                  (RSIZE  1  ?SIZE)
                                  (DAT69  REAM  ?C9)
(RSIZE  ?A  ?B)  ←  (ASK-USER  (SOURCE  ?A)
                                  (TARGET  ?B)
                                  (QUESTION  PLEASE SPECIFY THE
                                  NEAREST STANDARD REAMER SIZE
                                  CORRESPONDING TO A DIAMETER  ?A))
(DEFELAB  RSIZE  (THERE ARE STANDARD REAMERS AVAILABLE FROM
                      6 MM TO 40 MM WITH AN INCREMENT OF 1 MM)).
```

It should be clear from the above rules that, if the finish boring operation does not get satisfied the next rule which specifies reaming gets satisfied.

KNURLING:

If the operation to be performed requires knurling, it is asserted as to what type of knurling is required on the surface.

The two types of knurling that are possible are parallel knurling and diamond knurling. This helps in specifying the appropriate cutting tool.

```
(OPR613  KNURL ?KNL  3  ?FX13  ?FY13  ?FZ13) ←
                              (OP3  KNURL  ?FX13  ?FY13  ?FZ13)
                              (KNL-TL  ?KNL)
                              (DAT613  KNURL  ?C13)
(KNL-TL  ?KNL)  ←  (ASK-USER  (SOURCE)
                              (TARGET  ?KNL)
                              (QUESTION  PLEASE SPECIFY WHAT
                              TYPE OF KNURLING IS REQUIRED.
                              PARALLEL OR DIAMOND)).
```

EXTERNAL THREADING, INTERNAL THREADING AND TAPPING:

A feature defined as EXTHREAD gets exploded into rough turning and threading operations. The rough turning operation is established earlier to threading. Similarly, for INTHREAD, drilling is the primary operation and then tapping or threading follows. While establishing the thread cutting operation one also asks information about the direction of threads that is LH or RH.

```
(OPR612  EXTHREAD  ?DIR  5  ?FX12  ?FY12  ?FZ12) ←
                              (OP5  EXTHREAD ?FX12  ?FY12  ?FZ12)
                              (THRD-DIR  ?DIR)
                              (DAT612  EXTHREAD  ?FX12  ?FZ12 ?C12)
```

```
(THRD-DIR  ?DIR) ← (ASK-USER  (SOURCE)
                              (TARGET  ?DIR)
                              (QUESTION  PLEASE SPECIFY THE
                              DIRECTION OF THE THREADS LH OR RH)).
```

When the feature INTHREAD is specified, we have to specify a operation either threading or tapping. The decision regarding which operation to be performed is based on the availability of tools. If a standard tap is available, we go in for tapping as it is faster and easier compared to threading.

```
(OPR612  INTHREAD  TAP  1  ?FX12  ?FY12  ?FZ12) ←
                              (OP1  INTHREAD  ?FX12  ?FY12  ?FZ12)
                              (OP3  FACE  ?X3  ?Y3  ?Z3)
                              (TAP-OR-THREAD  ?FX12)
                              (DAT612  TAP  ?C12)
(TAP-OR-THREAD  ?TOT) ← (ASK-USER  (SOURCE  ?TOT)
                              (TARGET)
                              (QUESTION  PLEASE SECIFY YES IF THERE
                              IS A STANDARD TAP THAT IS AVAILABLE
                              CORRESPONDING TO A DIAMETER OF  ?TOT))
(DAT612  TAP  ?C12) ← (MATERIAL  ?M)  (HARDNESS ?H)  (TAPSPD ?M ?H ?C12)
```

```
(OPR612  INTHREAD  ?DIR  1  ?FX12  ?FY12  ?FZ12) ←
                          (OP1  INTHREAD  ?FX12  ?FY12  ?FZ12)
                          (THRD-DIR  ?FX12)
                          (DAT612  INTHREAD  ?FX12 ?FZ12 ?C12)
(DAT612  INTHREAD  ?FX12  ?FZ12  ?C12) ←
                          (THRDAT  ?FX12  ?FZ12  ?C12)
```

By looking at the above rules, it should be clear that tapping operation does not get satisfied, if the internal threading operation gets satisfied.

4.3 CONSULTATION WITH THE USER:

User has to interact with the system at various stages of developing the process plan. The interaction with the user has been facilitated by defining the predicates as of ASK-USER type. The ASK-USER predicate gets asserted as a fact after accepting the response from the user. If the user responds with DONTKNOW the question is not issued in future as well. It is also possible to attach text with an ASK-USER predicate. When the user responds with WHAT, the text is displayed to the user. It is possible to help the user respond correctly by explaining why the question is issued and also by giving him some recommended practice which helps in supporting his decision. Thus the ASK-USER predicates make it possible to gather as much information as possible from the user.

Initially some information is provided to the user and afterwards he starts describing the part in terms of features. The predicates OP1, OP2,..., OP6 here onwards called input predicates, are asserted when the user responds with the feature description. If the user forgets how to describe a feature, he can type WHAT and look at the information, associated with that predicate. There are also predicates ST1, ST2, ..., ST6 which ask the user to respond with the surface finish and tolerance of the feature.

Information regarding the standard speeds and feeds that are available on a lathe are inferred through the user. This is essential because unless the determined speed and feed are corrected to the nearest standard speed and feed that are available on the lathe, they does not mean anything. Also information about the nearest standard drill size that is available in the workshop is asked when the feature requies drilling operation.

The user is also asked about some mandatory information which involves specifying the material of the workpiece, hardness range of the material, total length of the part and the maximum diameter at any position on the part. The various materials identified alongwith their code name and hardness range are shown in Tables 4.1 and 4.2.

Table 4.1: Material Code.

Material	Code Name
Plain Carbon and Low Alloy Steels	PCLS
Free Cutting Steels	FCS
High Speed Tool Steel	HSTS
Tungsten Hot Work Tool Steel	THWTS
Chromium Hot Work Tool Steel	CHWTS
Ferritic Stainless Steel	FRS
Austentic Stainless Steel	ASS
Martensitic Stainless Steel	MTS
Cast Iron	CIRON
Aluminium Alloys	ALUMIN
Copper Alloys	COPPER

Table 4.2: Hardness Range Code.

Hardness Range (H)	Code
$75 \leq H < 125$	75125
$125 \leq H < 175$	125175
$175 \leq H < 225$	175225
$225 \leq H < 275$	225275
$275 \leq H < 325$	275325
$325 \leq H < 375$	325375
$375 \leq H < 425$	375425

4.4 GOAL TREE GENERATION

When a process plan has to be generated for a part, PROCESS-PLAN has been set-up as the top goal. While inferring the top goal the system goes through various stages which are shown in Figure 4.1, which is generally known as the goal-tree. In order to satisfy the top goal, the tree has to be traversed and the type of tree traversal that is adopted in the present system is, the depth-first-search strategy.

If one carefully observes the goal tree, he can identify the various sub-goals that are to be satisfied. Initially, the system asks the user to respond to various questions which include specifying the speeds and feed that are available on the lathe, work piece material and hardness, total length of the workpiece etc. After this, the user is asked to describe each of the features of the part. Along with each feature description, information about surface finish and tolerance is also asserted. Once the part description is over, the system goes on finding the various operations and their sequence along with the recommended cutting conditions for each operation. After this, information regarding the tools for each operation, cutting fluid for each operation and the tool angles for a single point tool is inferred. Then the system collects all these relevant inferred data and generates the report which gives the sequence of operations, the recommended cutting conditions for each operation, the tools recommended for each

operation, the cutting fluid for each operation and also the recommended single point cutting-tool angles. It also gives the statistics like total machining time and the time for which each tool is required.

The working of the system would be more clear if one looks at the sample output for the part shown in the Fig. 4.2, which is attached herewith.

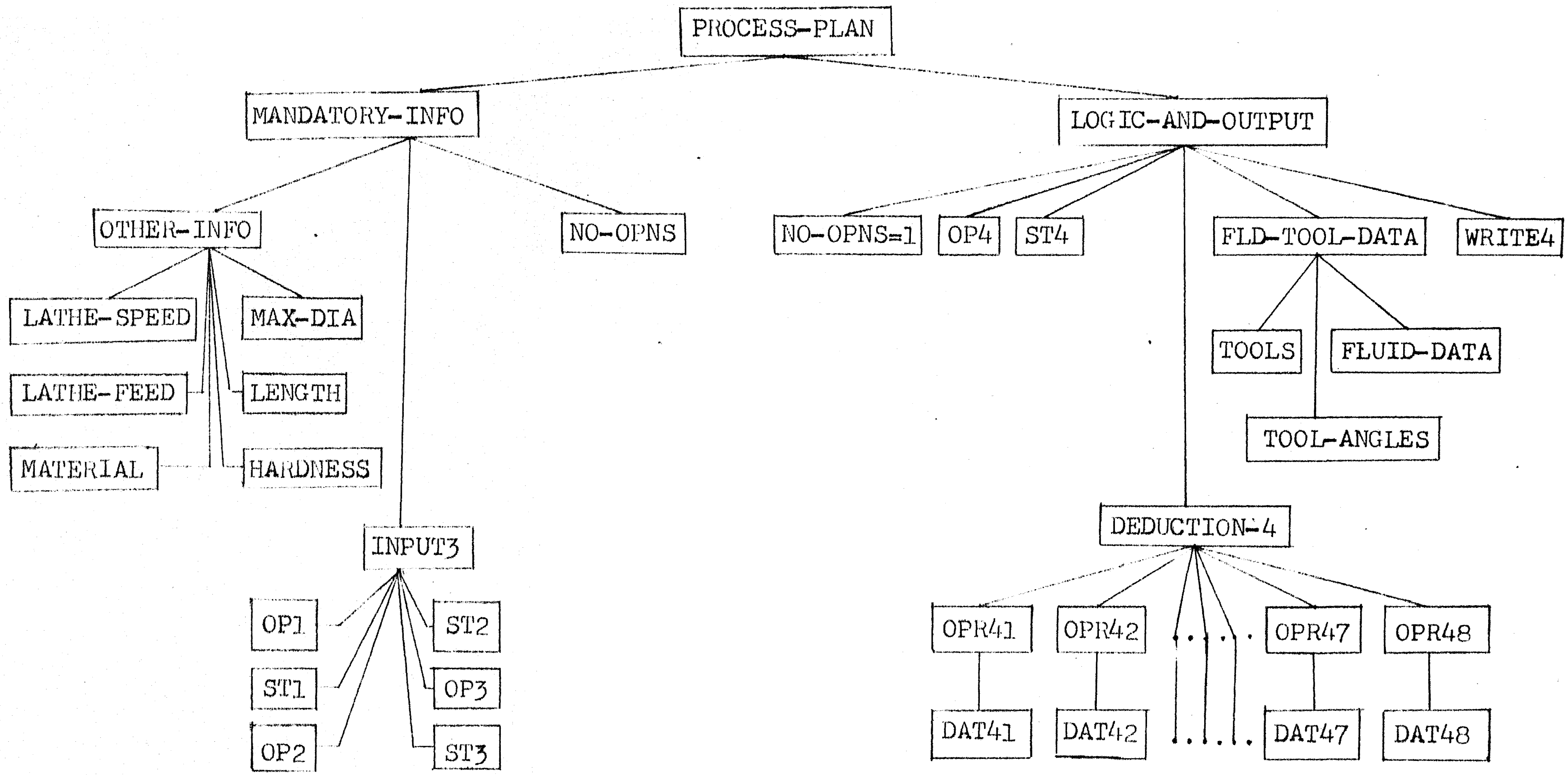

Figure 4.1: Goal Tree.

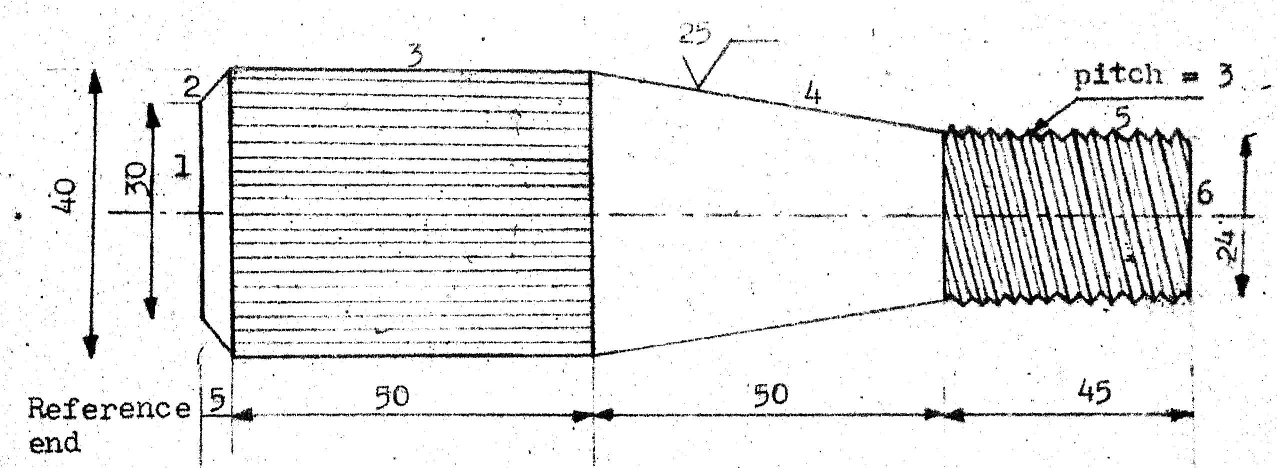

Fig. 4.2: Sample Part.

```
RECORD FILE DSK: FIT OPENED 06-FEB-87 05:10:39
NIL
<14>GOAL(PROCESS-PLAN)
(QUESTION IF YOU WANT TO KNOW SOME DETAILS BEFORE WORKING WITH THE SYSTEM TYPE
YES ELSE TYPE NO) >YES
     HELLO USER ! THIS SYSTEM GENERATES PROCESS PLAN FOR AXI-SYMMETRIC PARTS *
TO PRODUCE THE PROCESS PLAN IT IS REQUIRED THAT THE PART IS DESCRIBED IN TERMS
OF FEATURES * THE FEATURES THAT ARE IDENTIFIED BY THE SYSTEM ARE :=. FACE | CYL
| EXTAPER | INTAPER | EXTHREAD | INTHREAD | HOLE | KNURL | FORM
     THE PART HAS TO BE DESCRIBED AFTER FIXING UP A REFERENCE END AND NUMBERING
THE VARIOUS FEATURES IN A PARTICULAR ORDER * THE FOLLOWING RULES ARE TO BE
FOLLOWED FOR DOING THE SAME * THEY ARE :=.
     I    THE REFERENCE END IS ANY ONE OF THE TWO ENDS OF THE PART AND IT SHALL
BE LOCATED IN SUCH A WAY THAT THE DISTANCE BETWEEN THE REFERENCE END AND THE
EDGE CORRESPONDING TO THE SURFACE WITH MAXIMUM EXTERNAL DIAMETER IS MINIMUM
     II   IF THE PART HAS A THROUGH HOLE OR THE INTERNAL FEATURE OPENS AWAY FROM
THE REFERENCE END THEN THE INTERNAL FEATURE NEAR TO THE REFERENCE END IS
NUMBERED ONE * STARTING FROM THIS FEATURE MOVING TOWARDS THE RIGHT IN CLOCKWISE
DIRECTION NUMBER ALL THE REMAINING FEATURES
     III  IF THE PART HAS INTERNAL FEATURES WHICH OPEN IN THE DIRECTION OF THE
REFERENCE END THEN THE INNERMOST FEATURE IS NUMBERED ONE * STARTING WITH
THIS FEATURE MOVING TOWARDS LEFT IN ANTI-CLOCKWISE DIRECTION NUMBER ALL THE
REMAINING FEATURES

(QUESTION IF YOU HAVE LOCATED THE REFERENCE END AND NUMBERED ALL THE FEATURES
FOR FURTHER DETAILS TYPE YES) >YES
```

```
        EACH FEATURE IS DESCRIBED AS FOUR PARTS WHERE THE FIRST PART IS THE
FEATURE HEADING AND THE REMAINING THREE PARTS ARE THE DIMENSION DETAILS
        < HEREAFTER THE REFERENCE END WILL BE REFFERED TO AS REND >
        THE VARIOUS FEATURES ARE DESCRIBED AS GIVEN BELOW :=
        CYL        ---  DISTANE FROM REND * LENGTH *DIAMETER
        FACE       ---  DISTANCE FROM REND * OUTER DIAMETER * INNER DIAMETER
        EXTAPER    ---  DIAMETER NEAR TO REND * LENGTH * OTHER DIAMETER
        INTAPER    ---  DIAMETER NEAR TO REND * LENGTH * THE OTHER DIAMETER
        EXTHREAD   ---  NOMINAL DIAMETER * LENGTH * PITCH OF THREAD
        INTHREAD   ---  NOMINAL DIAMETER * LENGTH * PITCH OF THREAD
        HOLE       ---  HOLE DIAMETER * LENGTH * DISTANCE FROM REND
        KNURL      ---  DISTANCE FROM REND * LENGTH * DIAMETER
        FORM       ---  DISTANCE FROM REND * LENGTH * MAX OUTER DIAMTER
     |*| ALL DIMENSIONS ARE TO BE IN MM |*|
(QUESTION IF YOU ARE READY WITH THE VARIOUS PART DETAILS TYPE YES TO INTERACT
WITH THE SYSTEM) >YES
(QUESTION PLEASE SPECIFY THE VARIOUS SPINDLE SPEEDS THAT ARE AVAILABLE ON THE
LATHE IN THE FORM OF A LIST) >(45 56 70 110 137 170 215 270 325 420 525 655
820 1025 1280 1600 2000)
(QUESTION PLEASE SPECIFY THE VARIOUS FEEDS THAT ARE AVAILABLE ON YOUR LATHE IN
THE FORM OF A LIST) >(0.05 0.068 0.75 0.90 0.10 0.125 0.150 0.158 0.175 0.20
0.225 0.250 0.300 0.350 0.40 0.450 0.500)
(QUESTION PLEASE SPECIFY THE VARIOUS CROSS FEEDS THAT ARE POSSIBLE ON THE LATHE
) >(0.03 0.042 0.046 0.050 0.060 0.100 0.130 0.166 0.183 0.230 0.260 0.330 0.355
0.40 0.430)
```

(QUESTION PLEASE ANSWER YES IF THE PART IS PRODUCED FROM BAR STOCK ELSE ANSWER NO) >YES

THE WORK MATERIAL IS TO BE SPECIFIED USING THE CODE AS DESCRIBED BELOW :-

* MATERIAL *	* CODE *
PLAIN CARBON AND LOW ALLOY STEELS	PCLS
FREE CUTTING STEELS	FCS
HIGH SPEED TOOL STEEL	HSTS
CHROMIUM HOT WORK TOOL STEEL	CHWTS
TUNGSTEN HOT WORK TOOL STEEL	THWTS
FERRITIC STAINLESS STEEL	FRS
AUSTENTIC STAINLESS STEEL	ASS
MARTENSITIC STAINLESS STEEL	MTS
CAST IRON	CIRON
COPPER AND ITS ALLOYS	COPPER
ALUMINIUM AND ITS ALLOYS	ALUMIN

(QUESTION LOOKING AT THE ABOVE INFORMATION PLEASE SPECIFY THE PART MATERIAL) >FC

THE BRINELL HARDNESS NUMBER OF THE MATERIAL IF FALLS WITHIN THE RANGE SPECIFIED BELOW THEN MENTION THE RANGE AS SHOWN :-

* HARDNESS RANGE *	* CODE *
(BHN > 75) AND (BHN <= 125)	75125
(BHN > 125) AND (BHN <= 175)	125175
(BHN > 175) AND (BHN <= 225)	175225
(BHN > 225) AND (BHN <= 275)	225275
(BHN > 275) AND (BHN <= 325)	275325

```
        (BHN > 325) AND (BHN <= 375)          325375
        (BHN > 375) AND (BHN <= 425)          375425
(QUESTION PLEASE SPECIFY THE RANGE IN WHICH THE BRINELL HARDNESS NUMBER OF THE
MATERIAL MENTIONED ABOVE FALLS BY LOOKING AT THE GIVEN INFORMATION) >275325
(QUESTION SPECIFY THE TOTAL LENGTH OF THE PIECE THAT IS BEING WORKED) >150
(QUESTION PLEASE SPECIFY THE MAX DIAMETER VALUE AT ANY PLACE OF THE WORK-PIECE)>40
(QUESTION PLEASE SPECIFY THE FIRST FEATURE DETAILS AS DESCRIBED EARLIER) >FACE 0 30
(QUESTION PLEASE SPECIFY THE SURFACE FINISH IN MICRO-INCHES AND TOLERANCE IN MM
 ** IF YOU DO NOT KNOW ANY OF THE VALUES TYPE 0) >0 0
(QUESTION PLEASE SPECIFY THE SECOND FEATURE DETAILS PROPERLY AS DESCRIBED
EARLIER) >EXTAPER 30 5 40
(QUESTION PLEASE SPECIFY THE SURFACE FINISH IN MICRO-INCHES AND TOLERANCE IN MM
 ** IF YOU DO NOT KNOW ANY OF THE VALUES TYPE 0) >0 0
(QUESTION PLEASE SPECIFY THE THIRD FEATURE DETAILS PROPERLY AS DESCRIBED
EARLIER) >KNURL 5 50 40
(QUESTION PLEASE SPECIFY THE SURFACE FINISH IN MICRO-INCHES AND TOLERANCE IN MM
 ** IF YOU DO NOT KNOW ANY OF THE VALUES TYPE 0) >0 0
(QUESTION PLEASE SPECIFY THE TOTAL NUMBER OF REMAINING FEATURES) >3
(QUESTION PLEASE SPECIFY THE FOURTH FEATURE DETAILS PROPERLY AS DESCRIBED
EARLIER) >EXTAPER 40 50 24
(QUESTION PLEASE SPECIFY THE SURFACE FINISH IN MICRO-INCHES AND TOLERANCE IN MM
 ** IF YOU DO NOT KNOW ANY OF THE VALUES TYPE 0) >25 0.05
(QUESTION PLEASE SPECIFY THE FIFTH FEATURE DETAILS PROPERLY AS DESCRIBED
EARLIER) >EXTHREAD 24 45 3
(QUESTION PLEASE SPECIFY THE SURFACE FINISH IN MICRO-INCHES AND TOLERANCE IN MM
```

```
** IF YOU DO NOT KNOW ANY OF THE VALUES TYPE 0) >40 0.10
(QUESTION PLEASE SPECIFY THE SIXTH FEATURE DETAILS PROPERLY AS DESCRIBED
EARLIER) >FACE 200 24 0
(QUESTION PLEASE SPECIFY THE SURFACE FINISH IN MICRO-INCHES AND TOLERANCE IN MM
 ** IF YOU DO NOT KNOW ANY OF THE VALUES TYPE 0) >0 0
(QUESTION PLEASE SPECIFY THE MATERIAL OF THE CUTTING TOOL ** CARBIDE OR HSS) >WHAT
(FOR OPERATIONS LIKE TURNING & BORING CARBIDE TOOLS ARE GENERALLY PREFERABLE *
HOWEVER HSS TOOLS ALSO CAN BE USED BUT THEY ARE PREFERRED FOR OPERATIONS LIKE
DRILLING AND REAMING)>CARBIDE
(QUESTION PLEASE SPECIFY THE MAXIMUM DEPTH OF CUT IN MM THAT IS ALLOWABLE ON
THE MACHINE TOOL CONSIDERED) >WHAT
(THE MAXIMUM DEPTH OF CUT IS DEPENDENT ON MACHINE-TOOL CAPACITY, TOOL MATERIAL ,
WORK MATERIAL AND MANY OTHER VARIABLES * BUT IN GENERAL A VALUE BETWEEN 2.5 TO  4
 MM IS USED)>3.0
(QUESTION PLEASE SPECIFY THE NEAREST BAR DIAMETER CORRESPONDING TO A DIAMETR OF
40 MM)>WHAT
(THE STANDARD BAR DIAMETERS THAT ARE GENERALLY AVAILABLE ARE 8 11 16 23 31 34 38
50 64 89 114 139 165 200)>50
(QUESTION PLEASE SPECIFY THE TYPE OF THREADS LH OR RH)>RH
```

THE SEQUENCE OF OPERATIONS IS GIVEN BELOW:

SR NO	OPERATION	CORRESPONDING FEATURE
1	FACING	6
2	ROUGH TURNING	3
3	ROUGH TURNING	5
4	ROUGH TAPER TURNING	4
5	FINISH TAPER TURNING	4
6	EXTERNAL THREADING	5
7	KNURLING	3
8	PARTING OFF	1
9	CHAMFERING	2
10	FACING	1

FOR THE SEQUENCE OF OPERATIONS SPECIFIED ABOVE THE RECOMMENDED CUTTING CONDITIONS ARE AS GIVEN BELOW:=

SR NO	CUTTING SPEED (MT / MIN)	SPINDLE SPEED (RPM)	FEED (MM / REV)	DEPTH OF CUT (MM)	NO OF PASSES	MACHINING TIME (MIN)
1	134	320	0.380	0.380	1	0.090
2	123	320	0.250	2.180	2	1.450
3	129	1025	0.300	2.450	3	0.430
4	129	1025	0.300	2.450	3	0.290
5	134	1025	0.175	0.640	1	0.270
6	42	525	-----	0.250	10	0.280
7	39	325	0.050	-----	---	0.800
8	51	420	0.050	-----	---	0.790
9	51	420	0.100	-----	---	0.410
10	134	1420	0.380	0.380	1	0.800

THE TOTAL MACHINING TIME IS := 4.050

THE CUTTING TOOL DETAILS FOR THE SEQUENCE OF OPERATIONS GIVEN ABOVE ARE AS FOLLOWS:=

SR NO	TOOL TYPE	TOOL MATERIAL	I S TOOL CODE
1	RH FACING TOOL	CARBIDE	ISO 5 -R 3232 IS:2163
2	STRAIGHT TURNING TOOL	CARBIDE	ISO 1 -R 1516 IS:2163
3	STRAIGHT TURNING TOOL	CARBIDE	ISO 1 -R 1516 IS:2163
4	CRANKED TURNING TOOL	CARBIDE	ISO 2 -R 1212 IS:2163
5	CRANKED TURNING TOOL	CARBIDE	ISO 2 -R 1212 IS:2163
6	POINTED TURNING TOOL	CARBIDE	ISO 1 -2012 IS:2163
7	PARALLEL KNURLING TOOL		
8	PARTING OFF TOOL	CARBIDE	ISO 7 -R 2516 IS:2163
9	CHAMFERING TOOL		
10	RH FACING TOOL	CARBIDE	ISO 5 -R 3232 IS:2163

THE RECOMMENDED SINGLE POINT CUTTING TOOL GEOMETRY IS :=

TOOL MATERIAL	BACK RAKE	SIDE RAKE	END RELIEF	SIDE RELIEF	SIDE AND EDGE CUTTING ANGLE
CARBIDE	-5	-5	5	5	15

THE RECOMMENDED CUTTING FLUIDS ARE :=

OPERATIONS	CUTTING FLUID
6	MEDIUM SULPHURIZED FATTY OIL
1 2 3 4 5 8 9 10	SOLUBLE OIL
7	LARD OIL

THE TIME FOR WHICH EACH TOOL IS REQUIRED IS GIVE BELOW :-

TYPE OF TOOL	TIME (MIN)
RH FACING TOOL	0.120
STRAIGHT TURNING TOOL	1.890
CRANKED TURNING TOOL	0.560
POINTED TURNING TOOL	0.280
PARALLEL KNURLING TOOL	0.300
PARTING OFF TOOL	0.790
CHAMFERING TOOL	0.110

```
T
<15>RECORDFILE
RECORD FILE DSK: FIT CLOSED 06-FEB-87 05:17:52
```

CHAPTER V

CONCLUDING REMARKS

5.1 CONCLUSIONS

An attempt has been made to build an expert system which can produce process plans for axi-symmetric parts. Standard features have been identified which help the system understand the part described by the user. The present system is capable of generating the sequence of operations, recommended cutting conditions for each operation, recommended tools and cutting fluids for each operation and the recommended single point cutting tool angles. Also some statistics like total machining time and the time for which each tool is required are also presented.

The present system incorporates more than 350 facts and 200 rules. The system can generate process plans for parts which can be described starting from three features upto six features. The system is implemented on DEC-1090 at IIT, Kanpur.

In the present work, the idea is to see whether the latest developments in AI techniques can be applied to the manufacturing environment. Looking in this angle, we feel that the expert systems concept has a great potential in helping the industry, provided the vast ocean of unstructured knowledge

is acquired and organised into sets of rules and facts. This, however, seems to be a difficult task.

It is felt that a production system, in which the rules are conditional i.e., of IF-THEN type, is better suited for representing the knowledge related to manufacturing processes and operations. The shell at present does not have the capacity to explain or reason. This feature once incorporated can make the expert system complete.

5.1 SCOPE FOR FUTURE WORK

It is possible to generate several feasible sequence of operations for a given part. Hence, the present work can be extended to generate several such sequences and evaluate them on the basis of either minimum total cost of production or maximum production rate. This would result in the optimum sequence of operations.

The present concepts can be extended for the case of prismatic parts by identifying some more features in addition to those already mentioned. It would be more difficult for prismatic parts because, the sequence of operations depend to a large extent on the type of machine tool and the jigs and fixtures that are available.

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APPENDIX A

Manual for
VIDHI - An Expert Systems Shell

Rajeev Sangal
Dept. of Computer Science and Engg.
Indian Institute of Technology Kanpur

Various commands for defining assertions, issuing goals, etc. are given below. For all the commands, the outermost parentheses may be omitted (if the command fits in one line).

To run the system type:

```
.R VIDHI
```

To get help type:

```
.HELP VIDMAN          ;To display this manual
.HELP VIDTUT          ;To display the tutorial
```

1. Adding Assertions to the Workspace

1.1 Adding Facts

Use any one of the following forms:

```
(DEFASRT <name> <formula>)
(DEFASSERT <name> <formula>)
```

Examples:

```
(DEFASRT F1 (ON A B))
(DEFASRT NIL (OVER A F))
DEFASRT F2 (ON B C)          ;If the outer parentheses
                             ; are dropped
```

UNDEFASRT is used to remove an assertion from the database. The search is carried out from the beginning first among the facts and then among the rules.

```
(UNDEFASSERT <name> <predicate>)
(UNDEFASRT <name> <predicate>)
```

UNDEFFACT or UNDEFRULE are like UNDEFASRT except that they remove a fact or a rule respectively.

1.2 Adding Rules

```
(DEFASRT <name> <consequent> <formula1> <formulan>)
(DEFASRT <name> <consequent>  <-
                  <formula1> ... <formulan>)
```

DEFASSERT can also be used instead of DEFASRT.

Examples:

```
(DEFASRT R1 (OVER ?X ?Y) <-
              (ON ?X ?Z) (OVER ?Z ?Y)))
```

2. Querying the Database

```
(GOAL <af1> ... <afn>)
```

where <afi>s are atomic formulas.

Examples:

```
GOAL (OVER A B) => YES

GOAL (OVER A ?Z) =>
     ?Z = B
     YES
GOAL (ON A ?U) (ON ?U C)   =>
     ?U = B
     YES
```

3. Storing a Workspace in Files

Before a workspace can be stored in files, it must be decided as to which predicates will be stored in what files. For this purpose, a catalog must be prepared for each of the files. After the catalogs are prepared, the file can be created or updated.

A file is specified by giving the name and the extension in a dotted list, or simply the name if there is no extension.

DEC-10 File	LISP specification
XPRT.DB	(XPRT . DB)
XPRT	XPRT

[Note: A file is specified fully by:

```
(<device> <ppn> <name>)
```

For example,

```
DSKD:   XPRT.DB [1,4]        (DSKD: (1,4) (XPRT.DB))
SYS:    XPRT.DB [1,4]        (SYS:  (1,4) (XPRT.DB))
SYS:    XPRT.DB              (SYS:  (XPRT.DB))
XPRT.DB [1,4]                (   (1 4)   (XPRT.DB))  ]
```

The following commands help prepare the catalog:

```
(ADDCAT <filename> <pred1> ... <predn>)
```

where <filename> is the name of a file, and <pred1> to <predn> are the names of predicates. It enters <pred1> to <predn> into the catalog for the file named <filename>. For example, the following:

```
(ADDCAT BLOCKS ON OVER)
(ADDCAT BLOCKS DO-GRASP)
```

first enters ON and OVER and then DO-GRASP to the catalog for file BLOCKS.

3.2 REMCAT

This is similar to ADDCAT except the predicates are removed from the catalog. For example,

(REMCAT BLOCKS OVER)

removes OVER from the catalog.

3.3 PPCAT

(PPCAT <filename>)

This displays the current catalog for the file named <filename>.

3.4 DSKOUT

The three commands described above operate on the catalog only. Actual file is not altered or created by them. Once the catalog is created (or updated, if one already exits), file can be created (or updated) using DSKOUT.

(DSKOUT <filename>)

The above causes information (facts, rules, dontknows, etc.) pertaining to predicates in the catalog for the <filename> to be written out to the file. The catalog is also included in the file.

3.5 DSKIN

DSKIN may be used to read a file created using DSKOUT or by saving a session (to be described later).

(DSKIN <filename>)

causes the file named <filename> to be read in. If the file was created using DSKOUT, it contains a catalog of predicate names, followed by relevant information involving the predicates. DSKIN causes the catalog as well as the information involving the predicates to be read in.

3.6 Examples

(1) Creating a file for predicates ON and OVER for the first time:

(ADDCAT BLOCKS ON OVER)
(DSKOUT BLOCKS)

(2) Reading a file that had been created earlier using DSKOUT:

(DSKIN BLOCKS)

(3) Updating information associated with predicates in a file:

```
(DSKIN BLOCKS)
 ....   ; Making changes to facts and
        ; rules relating to ON and OVER
(DSKOUT BLOCKS)
```

(4) Adding new predicates to a file:

```
(DSKIN BLOCKS)
 ...    ; Defining assertions relating to DO-GRASP
(ADDCAT BLOCKS DO-GRASP)
(DSKOUT BLOCKS)
```

4. Posing Questions

Questions can be posed using a special built-in predicate called ASK-USER. The following is its most general form:

```
(ASK-USER
  (SOURCE <var1> ... <varm>)
  (TARGET <var1> ... <varn>)
  (QUESTION      ... )
  (TYPES <type1> ... <typen>))
```

where <vari>s are the variables, and <typei>s are the type specifications of the target variables (for user responses).

To determine the truth value of a formula with the predicate ASK-USER, first it is checked that each of the source variables has a variable-free (i.e., value of the variable is not a variable and does not contain a variable), and none of the target variables has a value (other than a variable). If any of the checks fails, a failure is returned. If the checks succeed, the question is issued (after substituting variables, if any, in the question text) and user response is awaited.

If the number of target variables is zero, the user must answer in YES TRUE, NO or FALSE. The former two cause true to be returned. The latter two, on the other hand, cause failure of the formula.

If the number of target variables is non-zero, the user must answer with as many values (separated by spaces) Moreover, the values must satisfy the type specification. If so, the target variables are bound to the user response, and true is returned. The user can say DONTKNOW if he does not know the answer to the question. That causes failure of the formula, however, and the DONTKNOW is stored.

The type specifications are as follows:

T — no restriction on type

NUMBER — number

(RANGE <lower> <upper>)
Range of the number

(TOLERANCE <mean> <variation>)
Range (<mean> - <variation>) and (<mean> + <variation>)

(ENUMERATE <V1> ... <Vk>)

	list of values <V1> to <Vk> that the answer might take
<type-pred>	name of the predicate to be applied to the value to test its type

The type specifications are optional, in ASK-USER. If absent there are no restrictions on user responses. As an example, consider the following:

```
(ASK-USER
   (SOURCE ?X)
   (TARGET ?VAL)
   (QUESTION WHAT IS THE TEMPERATURE OF
        ?X IN DEGREES CENTIGRADE)
   (TYPES NUMBER))
```

The question with the given text is issued when ?X has a variable- free value and ?VAL does not have a (non-variable) value. The user must respond with a number (or DONTKNOW). If we want to restrict the number to be within some range we write the following;

```
(ASK-USER
   (SOURCE ?X)
   (TARGET ?VAL)
   (QUESTION   ... WHAT IS THE TEMPERATURE OF ?X IN
     DEGREES CENTIGRADE)
   (TYPES (RANGE 0 110)))
```

A number of commands are available. They are displayed if the user types HELP.

```
DONTKNOW      - If you do not know the answer.
REPEAT        - To see the question again.
WHAT          - To see elaboration of the question.
SHOW <pred> - To see facts stored for predicate <pred>.
TOP <cmd>     - To execute any top level command <cmd>.
HELP          - To see this message.
YES NO TRUE
   or FALSE   - when the question expects a confirmation or
                otherwise.
Values        - As many as needed by the question, separated
                by spaces.
```

5. DEFINTERMEDIATE and UNDEFINTERMEDIATE

(DEFINTERMEDIATE <pred1> ... <predn>)
(DEFINTMD <pred1> ...<predn>)

It defines predicates <pred1> to <predn> to be of intermediate type. Whenever a formula involving any of the predicates <predi>s is inferred, it is added to the database of facts. It helps avoid repeated derivations of the same formula. UNDEFINTERMEDIATE or UNDEFINTMD takes similar arguments but removes intermediate type for the predicate.

6. DEFELABORATION and UNDEFELABORATION

(DEFELABORATION <pred> (... <text> ...))

(DEFELAB <pred> (... <text> ...))

The above commands store the text with the predicate <pred>. It is issued when the user types WHAT in response to a question. UNDEFELABORATION or UNDEFELAB does the opposite of DEFELABORATION.

7. DEFCOMPUTEPRED and UNDEFCOMPUTEPRED

(DEFCOMPUTPRED <pred> <lambda>)
(DEFCOMP <pred> <lambda>)

It defines the predicate <pred> to be of computational type, and stores the function <lambda> with the <pred>. UNDEFCOMPUTEPRED or UNDEFCOMP does the opposite of DEFCOMPUTEPRED.

8. Saving and Restoring Sessions

During a session facts may get altered or dontknow information may get generated. Consequently, to save the session in a file, the facts and dontknow information is stored in a file. In the following:

(DSKOUT-SESSION <filename> <sessionfile>)

Facts and dontknow pertaining to predicates in the catalog of <filename> is stored in <sessionfile>.
The session may be restored later by:

(DSKIN <sessionfile>)

A session may be reset by

(RESET-SESSION <filename>)

which first causes all the relevant facts and dontknows to be removed from the workspace, and then the file <filename> is read back in.

9. Handling Errors

If you wish to stop the execution at any time type two control-C s. Execution stops and help can be obtained by typing '?'. Typing a control-D after two control-Cs takes you to the top level of LISP. A control-X after control-Cs takes you out of LISP. Session will be lost. (You can reenter LISP in the same session, if the very next command is CONTINUE OR CONT.)

10. Miscellaneous

To look at the information associated with predicates:

(PP <pred1> ... <predn>)

To increase space by <n> words, issue the following command:

```
(EXPFS <n>)
```

A reasonable number is 3000.
Memory for the storage of symbolic atoms can be increased similarly:

```
(EXPFWS <n>)
```

A reasonable number is 1000.
To see the predicates for which assertions have been defined, but which have not been saved in a file:

```
(CHANGES)
```

To save a session in a file do the following:

```
(RECORDFILE <filename>)

    ... session ...

(RECORDFILE)
```

To display a file on the terminal:

```
(TY <filename>)
```

11. Glossary of Built-in Predicates and Functions

11.1 Builtin Predicates

ASK-USER	- For issuing questions to the user. See VIDHI Tutorial.
(= <t1> <t2>)	- Equality predicate is true if the terms <t1> and <t2> are equal.
<, >, <=, >=	- Relational predicates with their usual meanings.
(ASSERTA <formula>)	- Asserts a fact <formula> at the beginning of the database.
(ASSERTZ <formula>)	- Asserts a fact <formula> at the end.
(RETRACTA <formula>)	- Remover a fact <formula> by searching for it from the beginning.
(RETRACTZ <formula>)	- Removes a fact <formula> from the end.

11.2 Builtin Functions

+	- add
-	- subtract
*	- multiply
/	- divide
any LISP function	

APPENDIX B

DATA TABLES

Some of the data tables that are used in making the fact database are given here.

Table 1: Recommended Cutting Speed for Turning Operations.

		Cutting Speed m/min.			
		Depth of cut, mm			
		0.1-0.4	0.4-2.5	2.5-4.5	4.5-10
		Feed mm/rev.			
Work Material	Tool Material	0.05-0.125	0.125-0.375	0.375-0.75	0.75-1.25
Plain Carbon and Low Alloy Steels	HSS	-	65-90	430-60	20-35
	CARBIDE	210-360	165-210	120-165	60-120
Free Cutting Steels	HSS	-	75-105	50-75	25-45
	CARBIDE	225-450	180-225	135-180	105-135
High Alloy Steel	HSS	-	50-75	35-50	20-30
	CARBIDE	150-225	120-150	105-135	60-90
Stainless Steels	HSS	-	30-45	25-30	15-20
	CARBIDE	110-150	90-110	75-90	50-75
Cast Iron	HSS	-	25-45	18-30	12-27
	CARBIDE	90-180	45-135	30-105	22-75
Aluminium and Alloys	HSS	105-150	65-105	45-65	30-45
	CARBIDE	210-300	135-210	90-135	60-90
Copper and Alloys	HSS	-	80-105	65-80	45-65
	CARBIDE	210-240	180-210	150-180	120-150

(Source: HMT, Production Technology, Ref. 9).

Table 2: Recommended Speed and Feed for Drilling Operations.

Work Material	Hardness Range	Cutting Speed (m/min.)	Feed mm/rev. 1/8	1/4	1/2	3/4	1	$1\frac{1}{2}$	2
Plain Carbon and low Alloy Steels	75-125	22.90	0.08	0.13	0.25	0.38	0.46	0.51	0.64
	125-175	20.30	0.08	0.13	0.25	0.30	0.36	0.46	0.53
	175-225	17.80	0.05	0.10	0.18	0.25	0.30	0.38	0.46
	225-275	14.00	0.05	0.10	0.16	0.25	0.25	0.33	0.41
	275-325	11.40	0.05	0.08	0.13	0.20	0.23	0.28	0.33
	325-375	8.90	0.05	0.08	0.13	0.20	0.23	0.25	0.28
	375-425	6.35	0.05	0.08	0.13	0.18	0.23	0.25	0.25
Free Cutting Steels	175-225	22.85	0.08	0.13	0.25	0.38	0.46	0.51	0.64
	225-275	22.85	0.08	0.13	0.25	0.38	0.46	0.51	0.58
	275-325	16.50	0.05	0.10	0.16	0.25	0.30	0.38	0.46
	325-375	10.15	0.05	0.08	0.16	0.20	0.23	0.25	0.28
	375-425	7.60	0.05	0.8	0.13	0.18	0.23	0.25	0.25
High Alloy Steels	175-225	10.15	0.05	0.08	0.13	0.20	0.23	0.28	0.33
	225-275	7.60	0.05	0.08	0.13	0.20	0.23	0.28	0.33
Stainless Steel	125-175	17.80	0.08	0.10	0.16	0.20	0.25	0.36	0.46
	175-225	15.25	0.05	0.08	0.16	0.20	0.25	0.36	0.46
	225-275	10.15	0.05	0.08	0.13	0.23	0.25	0.30	0.33
	275-325	8.90	0.02	0.05	0.08	0.13	0.16	0.20	0.23
	375-425	6.35	0.02	0.05	0.08	0.10	0.13	0.16	0.18
Aluminium and Alloys	-	152.40	0.25	0.36	0.43	0.43	-	-	-
Copper and Allpys	-	44.45	0.08	0.16	0.25	0.25	0.38	0.38	0.51

(Source: Metals Handbook, Vol. 3, Ref. 9).

(Note: Similar data table is available for reaming operations also.)

Table 3: Recommended Cutting Speed for Tapping.

Material	Hardness Range	Cutting Speed (m/min.)
Plain Carbon and Low Alloy Steels	125-175	11.40
	175-225	10.20
	225-275	8.90
	275-325	6.35
	325-375	5.10
	375-425	2.55
Free Cutting Steels	175-225	12.70
	275-325	8.90
	325-375	5.10
	375-425	2.55
High Alloy Steels	175-225	5.10
	225-275	3.80
Stainless Steels	125-175	8.90
	175-225	7.60
	225-275	5.10
	275-325	3.80
	375-425	2.55
Aluminium and Alloys	-	25.40
Copper and Alloys	-	15.25

(Source: Metals Handbook, Vol. 3, Ref. 9).

Table 4: Recommended Spindle Speeds and Number of Cuts for Threading Operations.

Diameter (mm)	Pitch (mm)	Spindle Speed (rpm)	Number of Cuts	
			External Threads	Internal Threads
30	4 2 1	450	11 8 6	15 13 9
42	5 3 2	400	12 10 8	17 15 13
72	6 4 3 2	220	17 12 10 8	21 15 13 11
100	6 4 3 2	160	17 12 10 8	21 15 13 11
140	6 4 3 2	125	17 12 10 8	21 15 13 11
200	6 4 3	110	17 12 10	21 15 13
250	6 4 3	80	17 12 10	21 15 13
250	6 4 3	80	17 12 10	21 15 13

(Source: HMT, Production Technology , Ref. 11).

(Note: Data is also available for various diameters other than those mentioned above).

Table 5: Recommended Cutting Fluids for Various Operations..

Machining Process	Plain carbon and low alloy steels and free cutting steels	Stainless Steels	High Alloy Steels	Aluminium Alloys	Copper Alloys
Tapping and Threading	3,4	4	4	1	6,1
Reaming	3,4	4	4	6	6
Drilling, boring and turning	7	9,7	9,7	7	8

Code No.	Fluid Name
1	Mild sulphurized fatty oil
2	Mild sulpho-chorinated oil
3	Medium sulphurized fatty oil
4	High sulphur fatty chlorinated oil
5	High chlorinated mild sulphurized oil
6	Fatty mineral oil
7	Soluble oil
8	Translucent soluble oil
9	Heavy duty soluble oil

(Source: HMT, Production Technology, Ref. 11).

Table 6: Recommended Tool Angles Based on Work Material, Hardness and Tool Material.

Work Material	Hardness BHN	Tool Material	Back Rake	Side Rake	End Relief	Side Relief	Side and Cutting Edge Angle
Plain carbon and low alloy steels, free cutting steels and high alloy steels	85 -225	HSS	10	12	5	5	15
		CARBIDE	- 5	- 5	5	5	15
	225-325	HSS	8	10	5	5	15
		CARBIDE	- 5	- 5	5	5	15
	325-425	HSS	0	10	5	5	15
		CARBIDE	- 5	- 5	5	5	15
Stainless Steels and Cast Iron	135-275	HSS	10	10	5	5	15
		CARBIDE	- 5	- 5	5	5	15
	275-325	HSS	5	8	5	5	15
		CARBIDE	- 5	- 5	5	5	15
	325-375	HSS	5	8	5	5	15
		CARBIDE	- 5	- 5	5	5	15
Aluminium Alloys	-	HSS	20	15	12	10	5
		CARBIDE	0	5	5	5	15
Copper Alloys	-	HSS	5	10	8	8	5
		CARBIDE	0	5	5	5	15

(Source: HMT, Production Technology, Ref. 11).